For Presentation at the 4th International Tesla Symposium, Colorado Springs, CO, July 26-29, 1990.

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FIRE BALLS, FRACTALS AND COLORADO SPRINGS:

A REDISCOVERY OF TESLA'S RF TECHNIQUES

by

K.L. Corum[*] and J.F. Corum, Ph.D.[**]

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ABSTRACT

In this paper, we recount how Tesla's 1899 Colorado Springs electric fire balls were produced and we document the phenomena with photographic evidence. As the Symposium participants will see, the solution to this mystery, like Poe's famous Purloined Letter, was placed by Tesla right before our eyes all the time. In this paper we shall discuss the following:

First, we note that a close examination of the Diary photographs of Tesla's RF oscillator reveals several surprising circuit configurations and even a fire ball event.

Secondly, we discuss the remarkable Soviet work of B.M. Smirnov and his Fractal theory of ball lightning. We conclude that Smirnov's analytical model provides a consistent description of the sort of fire balls which Tesla produced ninety years ago, and that the present experiments provide a documentation of Smirnov's Mandelbrot-Fractal theory of ball lightning.

Lastly, we take the audience into our laboratory to see our equipment, follow our procedures and see the photographic results of doing what Tesla told us to do and showed us to do - ninety years ago. We show color slides of glowing isolated fire balls, spectacular multiple fire ball events, and even ball lightning passing through a glass windowpane.

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INTRODUCTION

We have presented the engineering analysis of Tesla's electrical oscillators in many of our previous publications. In a companion paper presented at this year's ITS Symposium, we discuss the behavior of Tesla's circuit configurations for producing electric fire balls, and how we came to recognize that he was using multiple secondaries driven by one master primary. [Ref. 1] There are literally dozens of laboratory photographs and Diary sketches showing this configuration in action. [Ref. 2] (How could anyone have missed it?) Furthermore, perhaps the most famous picture ever printed of Tesla has a large fire ball in action.

We refer to Photograph XII on page 336 of the Diary, of course. Tesla sent a copy of this to William Crookes with the inscription, "To my dear friend, Sir William Crookes, whose correspondence I always read but never answer!" (If you look above the second coil from the right half way between the second and third studs to the left, along the upper path of the center forked discharge, you will see a fire ball, about 2 or 3 inches in diameter, skewered like a baseball on a sword.) Tesla reports making fire balls up to 1½ inches in diameter in the Diary (pg. 370), and from the 1914 Patent one is lead to believe that he produced even larger ones. We have published a collection of Tesla's Diary descriptions along with discharges and fire balls which we produced that matched his written description. [Ref. 3]

Explicitly following the RF technique given in the writings of Tesla, we began producing electric fire balls 2 cm in diameter, in air, during August of 1988. Tesla's work was performed 89 years earlier, during the summer of 1899, but has never been replicated or examined technically in the open literature. Although we found that fire ball production was repeatable in the laboratory and was easily documented with many photographs and real time video recordings (see Refs. 3,4,5), the physics behind their formation and evolution was not clearly understood by us at that time.

We had a high voltage RF process to produce this remarkable phenomenon on demand but we were lacking a clear explanation of the nature of the fire balls so produced. Tesla's detailed and remarkable observations of 1899 advance several hypotheses as to the nature of fire balls, but we have always felt that something more than turn-of-the-century physics is needed to clearly understand the phenomenon. Any progress in fire ball engineering would require an understanding expressed in more modern physical terms.

Although we were quite familiar with Kapitza's work and the surfeit of ball lightning publications generated by Western scientists over the past 150 years, we had never taken the opportunity to seriously examine the recent advances in Soviet ball lightning research.

RECENT SOVIET ADVANCES

In June of 1989 we became aware of the significant advances in ball lightning theory which have been published in the Soviet scientific literature. Much of the recent Soviet literature contains ball lightning speculations as unsatisfactory and bizarre as that appearing in the Western scientific journals. However, there is a remarkable thread of publications which, we believe, describes the Tesla method of ball lightning formation with surprising accuracy. We list these as References 6-25.

This theoretical approach has been developed to a mature and scholarly level primarily through the dedicated efforts of B.M. Smirnov and his colleagues at the Institute of Thermophysics, Siberian Branch of the Academy of Sciences of the USSR at Novosibirsk. (Professor Smirnov is now at the USSR Academy of Science's Institute of High Temperatures in Moscow.)

At the outset of his work, Smirnov recognized the futility of all ball lightning models that did not incorporate chemical energy storage. He also possessed a clear understanding of aerosols, aerogels, filamentary structures, plasma chemistry and dust particle combustion.

With the advent of the concept of fractals and the physics of diffusion limited aggregation (commonly referred to as DLA), in the late 1970's to mid 1980's (see References 26-33), Smirnov was able to extensively develop an aerogel analytical model in which the active substance of ball lightning is in the form of an electrically charged structure of interwoven submicron filaments - i.e, a porous fractal cluster of great internal chemical capacity. Almost the entire envelope filled by such an aerogel structure is occupied by vacant pores.

The energy release from a chemically charged fractal cluster can be described by a multistep process of combustion. For example, Smirnov proposes the multistep combustion of a charcoal fractal dust cluster, in ozone absorbed by it, as a model process in ball lightning:

$$(1) \qquad C + O_3 \longrightarrow X \xrightarrow{\alpha} Y \longrightarrow Z \xrightarrow{\beta} CO_2 \text{ , } CO$$

where the rate constants, α and β, of the slowest stages are saturation temperature dependent and, according to Smirnov's calculations, imply relatively long durations. According to Smirnov, "The combustion of charcoal in its absorbed ozone is an intensive and slow process of heat release." (Ref. 15) The multistep process is both intensive and slow. The predicted temperatures and lifetimes are consistent with ball lightning observations.

In Smirnov's model, the color and luminosity of the fire ball are produced in a manner similar to the presence of flare compounds used in pyrotechnics. Smirnov's remarkable analytical model has been able to satisfy every documentable property of ball lightning.

FRACTAL PHENOMENA AND THE ORIGINS OF BALL LIGHTNING

The "chemical history of a candle" has been a center of curiosity and delight since Faraday's noted Christmas lectures at the Royal Institution in the mid 19th century. His famous talks provide an unsurpassed introduction to the basic principles of combustion, and they are still available in print today. (Ref. 34) It was Faraday who pointed out the central role of soot and carbon particles to the flame's luminosity.

The recent development of fractal science has broadened our understanding of the formation of dust, soot, colloids and condensed aerosols. Studies of fractal growth have provided new insight to how soot grows by adding bits of carbon in a random coagulation.

In many respects, perhaps the seminal work relating fractals and smoke was the publication of the remarkable experimental investigation of Forrest and Witten. (Ref. 27) They examined ultrafine smoke particles (on the order of 80 Angstroms in diameter) and found that the particles stick together to form chain-like aggregates. Their laboratory experiments revealed that fractal structures are indeed produced, in a few tens of milliseconds, after the thermal explosion of materials.

Forrest and Witten's apparatus consisted of a tungsten filament electroplated with either iron or zinc. When the filament was rapidly heated by a short duration high current pulse the plated material vaporized off of the filament and formed a dense gas (metallic vapor) which was diffusion limited in the surrounding atmosphere. The dense gas was composed of more or less uniform spherical particles. The hot particles rapidly moved outward from the hot filament, came to rest in the ambient medium, due to collisions, and formed a spherical halo about 1 cm from the filament. At this distance the particles began to condense and stick together, forming chained aggregates which then settled onto an electron microscope slide which was then examined and the condensed vapor was found to possess fractal properties.

Smirnov's great insight was to realize that this fractal cluster could be extended to explain the structure and properties of ball lightning. So overwhelming is the evidence put forth by Smirnov and his associates that there can be little doubt that his extensive research and analysis provides the best physical explanation for ball lightning available in modern science.

Having first performed the laboratory production of ball lightning and then learning of Smirnov's extensive analytical work, we believe that our experiments, following Tesla's 1899 instructions, provide explicit support (if not direct verification) of Smirnov's remarkable ball lightning theory. Before describing the results, let us first discuss our apparatus and experimental procedures.

RF APPARATUS FOR THE PRODUCTION OF FIRE BALLS

The apparatus which we employed to produce the fire ball photographs for this article is shown in Figure 1. (The associated electrical parameters are tabulated in Table 1, so that others may replicate our work.) As discussed below, we actually found two methods for generating fire balls. One method utilizes two resonators, and the physics for this is considered below. The other method employs only one resonator as the secondary of a spark gap triggered (or pulsed) LC oscillator. The latter configuration was obtained simply by disconnecting the smaller high frequency resonator, L_3, in Figure 1. Let us consider this classical Tesla coil electrical configuration first.

There have been many descriptions and analyses of Tesla's oscillators, the first of substance being by Oberbek in 1895. (Ref. 35) More recent attempts, including some measured results, have been published in the Journal of Applied Physics, the IEEE Transactions on Nuclear Science, and the Review of Scientific Instruments. (The recent interest in Tesla coils has been spawned by the demand for high voltage sources to drive pulsed high field emission or explosive electron emission diodes for the production of high current Relativistic Electron Beams.) The literature on this topic is now fairly extensive.

However, it is our opinion that all of these descriptions are based on an erroneous analytical model for the RF circuitry, and leave much to be desired from an engineering point of view. (They treat the apparatus as a lumped circuit and entirely overlook the fact that the current distribution on the resonator stage is a quarter wave sinusoid with an Imax (and a Vmin) at the base and an Imin (Vmax) at the top.) It wasn't until we employed Schelkunoff's concept of "average characteristic impedance" and applied slow wave transmission line theory to Tesla's resonators that we were able to accurately predict the operation of the high voltage RF oscillator during the post spark epoch and the subsequent production of fireballs.

Our model is accurate enough to be used directly with the historic 1899 data in Tesla's own laboratory notebooks. Of course, it may also be used with modern data, and it faithfully predicts the measured waveforms published by recent authors (whose simple-minded models fail to recognize analytically the distributed nature of the resonators). [What we usually found was that the spark duration of recent researchers was far too long for the coupling coefficients which they were using - with the result that significantly more performance could have been obtained from their apparatus.]

The main part of Tesla's fire ball apparatus consists of a one-quarter wave length tall, slow wave helical resonator above a conducting ground plane. [The measured voltage distribution is a true replication of the first 90 degrees of $\sin(\beta z)$.] Our resonator is magnetically coupled to a spark gap oscillator, of high peak power (approximately 70 kW), operating at a frequency of 67 kHz. As with Tesla's fire ball notes, we employ tight magnetic coupling. The actual average power being delivered to the high voltage electrode was on the order of 3.2 kW (producing a 7.5 meter RF discharge). Tesla, of course, was running about 100 times the power which we could produce with our rather modest equipment.

OPERATION

The spark gap oscillator was set to 800 pulses per second and the spark duration was 100 microseconds. The secondary, or RF resonator, had a measured coherence time of 72 microseconds. This means that the induced incoherent polychromatic oscillations took 72 μs to build up a standing wave (or interference pattern), and create a high voltage on the top of the resonator:

$$V_{max} = S\, V_{min} \tag{2}$$

where S is the VSWR on the helical resonator. A Smith chart may be employed to conveniently display the operation of the high voltage section of the apparatus. (The theory of operation is developed in considerable detail in Refs. 36,37,38. Reference 39 even provides a computer assisted tutorial.)

Tesla's machines have several important advantages over other high voltage techniques (such as Van de Graaff and Marx generators). Tesla's apparatus not only attains high energy, but it also permits heavy duty cycles, i.e. - high repetition rates and high average power processing.

Following Tesla's instructions, a short piece of thick copper wire or a carbon electrode emanates from the side of the high voltage electrode. When the pointed electrode discharges, the RF resonator then releases its energy rapidly, in a burst. (Tesla noted in many places that the production of fire balls required a "sudden and powerful discharge".) The burst of energy released manifests itself in the shape of a spherical ball or what may be a fractal "bubble". Certainly, this method of fireball production results in the generation of soaring vaporized metal or carbon particles, not unlike Forrest and Witten's diffusion limited agglomeration.

Tesla's actual instructions were to use "the tip of rubber-covered cable or wire number 10" to "facilitate the pumping of the spark". (CSN page 173-174) We suppose that diffusion limited agglomerations result either from copper vapor (bursts from the wire) or from carbon vapor (from the wire insulation). As with SiO_2, condensed CuO_2 can form an aerogel under such circumstances.

The fractal ball formation is not significantly different from that observed by Forrest and Witten (except that it is charged by the high voltage terminal). By the way, old fashioned rubber insulation is loaded with soot.

Now, as Smirnov points out, merely creating the porus fractal bubble would not be sufficient to result in ball lightning with lifetimes in excess of a few milliseconds. Fractal formation was done with the soot in Faraday's candles - but other ingredients are necessary for the production of ball lightning lasting several seconds or more. We noted that the Tesla apparatus was a copious generator of ozone and other reactants. We believe that these reactants, and perhaps other chemicals, are quickly absorbed into the charged porous fractal bubble. The plasma temperature in the discharge region where the structure is formed is sufficient for the multistep combustion process to initiate.

EXPERIMENTAL OBSERVATIONS

Using the apparatus shown in Figure 1, we observed multitudes of fireballs with diameters ranging from a few millimeters up to several centimeters. Fire ball lifetimes typically ranged from one-half to several seconds. The colors ranged from deep red to bright white. The demise of some were often accompanied by loud reports, while others appeared to just fade out. It has often been hypothesized that there probably exist two population types of ball lightning. Our observations would seem to support this thesis.

Recording the phenomenon on photographic film was sometimes difficult with the techniques available to us. In some cases, video recording proved to be superior. Time durations could be estimated from the video frame rate. With standard movie film both the ASA rating and the shutter speed were too slow. However, still photography was often adequate. In a remarkable sequence of photographs, we were able to cause fire balls to emanate from the opposite side of a glass windowpane. (See Refs. 3,4)

Photograph 1 shows the globular structure of a single large bright isolated electric fire ball. The actual fire ball was approximately 1 cm in diameter. The physical structure is remarkably spherical, and this would seem to imply that surface tension must play some role in fire ball evolution. The slight but noticeable limb darkening, and the almost solid appearance, would seem to indicate that the fire ball is optically thick. The film was ASA 400 and the shutter speed was 1/4 second.

Photograph 2 shows a single large fire ball, about 2 cm in diameter being struck by a high voltage RF streamer. The picture was taken from about 12 feet away.

In Photograph 3, there are twin fireballs, created in close proximity, gliding off to the right being struck by separate streamers. (A bright point appears farther downstream along the main streamer.) The film was ASA 400 and the shutter speed was 1/4 second. The photo was taken from a position about 5 meters perpendicular to the spray of the discharge.

In Photograph 4, there are 2 large fireballs (about 2 or 3 cm in diameter), being struck in series by an RF discharge. The photograph was taken from about 4 meters away.

In our laboratory experiments, the fireballs generally formed near the high voltage resonator, and would dart outward from the streamer, either upward or downward. This would seem to fit the description of "kugelblitz" - ball lightning. (By way of contrast, **bead lightning** - or "perlschnurblitz" - is that phenomenon which occurs when a discharge channel breaks up into short luminous fragments, with the disconnected beads, or pearls, appearing to persist longer than the discharge channel. Clearly, the bead lightning phenomenon is **not** what we are observing.)

NTSC video recordings of the fireball evolution seem to indicate that the fireballs are "born" in the space near the electrode and are subsequently struck by streamers. They sometimes start out as a 6 mm sphere, which then begins to grow. The ball seems to then sit still, floating in space, while the streamer fades out. The floating ball is then struck by the next streamer and begins to grow larger. In one sequence, the ball is struck by 6 separate discharges, growing in size each time. One fireball grew from an initial 6 mm sphere into a 5 cm diameter fiery red globule, over a 1.0 second time interval. Some fireballs can be seen to spin, with moving dark patches (like sunspots). Some of the fireballs appear to be transparent, with the discharges darting through them. Several are observed to change colors as they evolve and eventually explode like Novae. As hypothesized above, placing a wax candle on the high voltage resonator clearly enhances fireball production.

Photograph 5 shows a spray of fire balls emanating from the high voltage terminal. Several have diameters in excess of 1 inch.

Photograph 6 shows four bright fire balls amid a spray of RF streamers.

Viewing the fire balls and streamers with a video tape recorder is a fascinating activity - the streamers often appear to have bright fluid matter being visibly ejected and moving along their length. This matter apparently adds to the size of the fire ball. First, fire balls began to appear from nowhere (ie., they were not on previous video frames). On subsequent frames several of the floating fire balls are struck by a high voltage discharge emanating from the terminal of the high voltage resonator. In later frames the streamer has passed, and faded out, leaving the struck fire balls somewhat larger and hotter.

From the video sequence, it is now apparent that, although most of the still photographs show fire balls in the streamer, like golf balls skewered on a sword, what is actually occurring is that the apparatus (running 800 breaks per second) produces a great many discharges per second. These discharges sequentially strike the fire balls often enough, during the shutter open interval, to give the photographs the appearance of fire ball creation in the streamers. The streamers actually jump from fire ball to fire ball in a dazzling display.

Video photography also permitted another fascinating opportunity. We were able to view faint variations in the luminosity distribution across the fire ball disc by video signal processing. In one particular case, a fire ball actually appeared to be surrounded by a glowing shell (similar to M-57, the Ring Nebula in the constellation of Lyra). The resultant signal enhancement reveals the greater apparent luminosity of the spherical envelope of the fire ball. Astrophysically, this only occurs with extremely hot O and B type stars. Photograph 7 was made from a video monitor and reveals another interesting property of fire balls - they give the appearance of passing through glass windows. We discuss this in greater detail below.

Photograph 8 is rather dramatic. It shows a dozen large spherical fiery globules all in a row, at various stages of evolution, being struck by one streamer. The fire balls start out as red dwarfs, pass through various colors and sizes, to a bluish-white giant stage. Some seemed to explode as "Novae" while others seemed to cool back as red giants. The film was ASA 400 and the shutter speed was 1/4 second. A charred wooden dowel was used in place of Tesla's "rubber covered wire #10 to pump the spark". The 30 cm diameter high voltage electrode can be seen off to the left.

ALTERNATIVE GENERATION PROCEDURES

We also report on alternative electrical techniques for producing the same results. There is a second method of fire ball production which is documented in the writings of Tesla. In the photographs of the Colorado Springs apparatus it is quite evident that Tesla often employed several helical resonators excited from the same primary. (Again, it is important to note that these are slow wave transmission line distributed resonators, and not describable by simple lumped circuit analysis. The resonant voltage rise is by VSWR.) It has been reported that Tesla once made the following remarks concerning fire ball production during his Colorado Springs experiments:

> "... *it became apparent that the fire balls resulted from the interaction of two frequencies, a stray higher frequency wave imposed on the lower frequency oscillations of the main circuit . . . This condition acts as a trigger which may cause the total energy of the powerful longer wave to be discharged in an infinitesimally small interval of time and at a proportionately tremendously great rate of energy movement which cannot confine itself to the metal circuit and is released into the surrounding space with inconceivable violence.*"
> (Refs. 40, 4)

Following Tesla's instructions, we employed a single primary and wired our apparatus as two synchronously excited high power RF resonators (as shown in Figure 1), the first at a frequency of 67 kHz and the second at 156 kHz. (The exact frequencies aren't critical.) The idea of using multiple oscillators in synchronism was used by Tesla at the turn of the century in a patented primitive "frequency hopping" spread spectrum communication system. The apparatus can be seen in dozens of photographs and circuit diagrams in Tesla's Colorado Springs Notes.

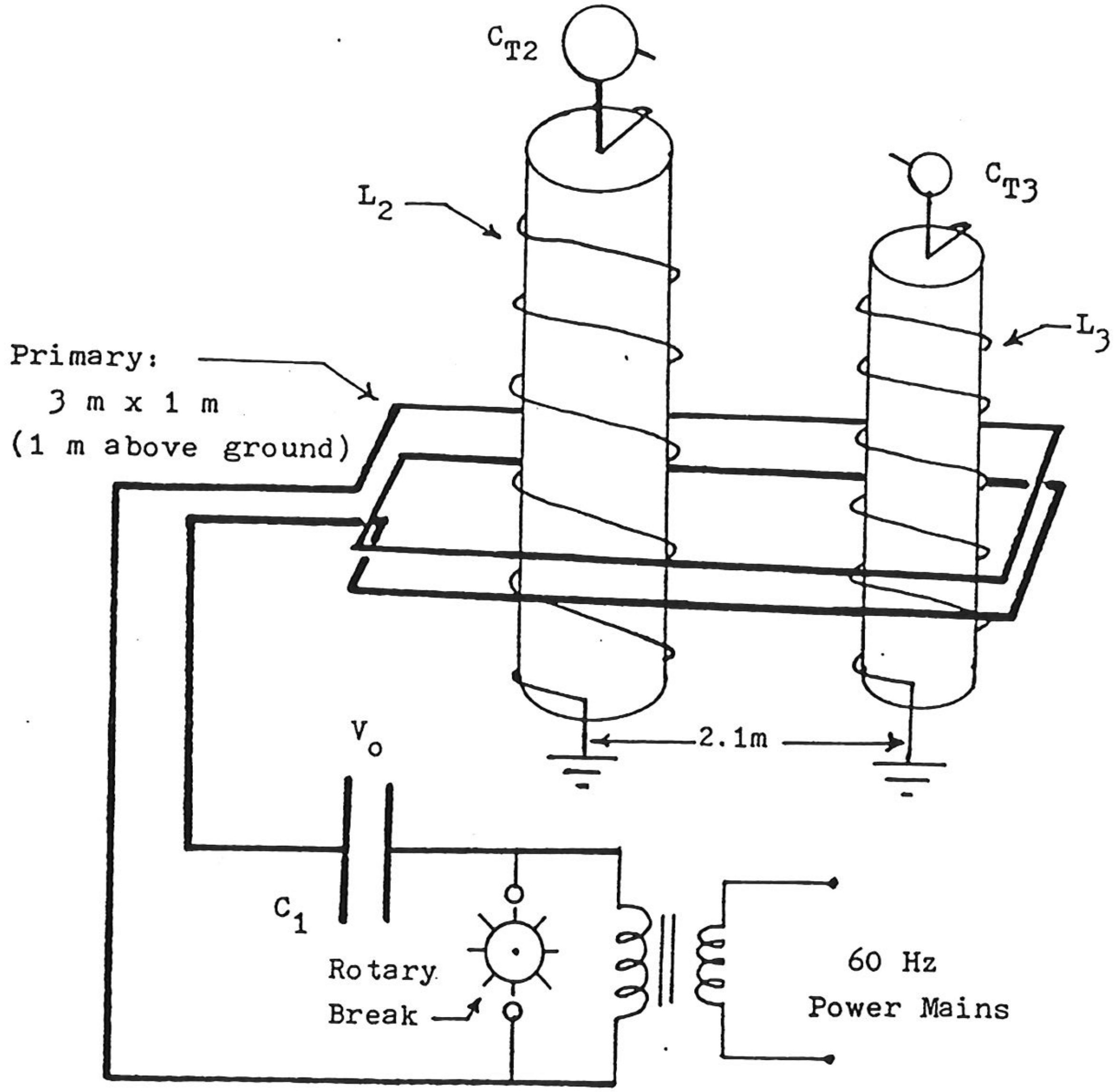


Figure 1. Tesla apparatus used to obtain the Photographs. Note the operation of the slow wave, RF, open helical resonators. Both resonators are excited by the same primary. The system was tuned so that after the primary spark broke, the low frequency quarter wave high resonator gave a maximum voltage of 2.4 MV at 66.6 kHz. The high frequency resonator attained 200 kV at 156 kHz. Specific lumped circuit and distributed resonator parameters are listed in Table 1 so that the reader may duplicate our experiments. The smaller high frequency resonator may be eliminated for some experiments.

TABLE I: Electrical and Physical Parameters for Figure 1

C_1 = .08 μF N_1 = 4 turns of three #2
L_1 = 65 μH d_{w1} = 0.375 inches stranded
R_1 = 2.0 Ohms

L_2 = 105 mH L_3 = 33.25 mH
C_2 = 54 pF C_3 = 31.2 pF
R_2 = 616 Ohms R_3 = 233 Ohms
M_{12} = 1300 μH M_{13} = 735 μH
N_2 = 780 turns N_3 = 432 turns
s_2 = 0.12 inches s_3 = 0.125 inches
$H_2 = N_2 s_2$ = 84 inches $H_3 = N_3 s_3$ = 54 inches
D_2 = 24 inches D_3 = 18 inches
d_{w2} = 0.103 inches d_{w3} = .125 inches
C_{T2} = 26 pF C_{T3} = 22 pF
$VSWR_2$ = 98 $VSWR_3$ = 118
C_{2-3} = static mutual capacitance of the resonators = 250 pF

Break speed = 800 BPS
Primary Spark Duration = 100 μs
V_o = 10 KV

s = turn-to-turn spacing   D = coil diameter
d_w = wire diameter C_T = electrode capacitance
H = coil length   R = RF loss resistance
VSWR = Resonator (coil) Voltage Standing Wave Ratio
C_2, C_3 = equivalent lumped capacitance of each resonator

The rather puzzling comments made above by Tesla now become transparent. Our experiments indicate that the relatively large low frequency resonator takes about 72 microseconds to build up its VSWR distribution to a peak of 2.4 MV, while the smaller high frequency coil builds up to a somewhat lower peak much more rapidly. This is discussed in greater detail in Appendix IV of Reference 39. Using the high frequency resonator to arc to the top of the low frequency resonator, where a high load impedance is normally seen, produces a rapid decrease in the load impedance of the low frequency slow wave structure. Due to the faster voltage rise on the high frequency helical resonator and the subsequent short duration arc to the low frequency resonator, the standing wave energy trapped in the large low frequency helical resonator will quickly "dump" into the reduced load impedance at the point of the arc. The low frequency resonator releases its energy rapidly, in a high current burst from the top electrode, or any projections on it. Circuit 4 on page 115 and the circuit on the top of page 174 of Tesla's notes (Ref. 2) are virtually the same as Figure 1 below. The general layout is seen in many of Tesla's photographs of the Colorado Springs laboratory.

Again, the fractal mechanism observed by Forrest and Whitten described above, and the excessive Ozone surrounding the apparatus, are probably responsible for Smirnov aerogel/fractal production and the resulting fire ball formation with this generator configuration employed by Tesla.

It has often been complained that "the current lack of any possibility of reproducing ball lightning reliably in the laboratory" forces us to study this phenomenon only by analyzing existing observations. Or, "Ball lightning will be successfully produced artificially only in very large experimental facilities (firing ranges, proving grounds, etc.)". (Ref. 12) The present photographic documentation of results produced by a rather modest (3.2 kW) replication of Tesla's apparatus shows that this is not at all the case. Even laboratories with small research budgets and very little modern instrumentation may carry out significant fire ball experiments.

APPARENT PASSAGE OF FIRE BALLS THROUGH GLASS WINDOWPANES

In an effort to go beyond the mere generation of electric fire balls, we have attempted to resolve another fundamental problem associated with ball

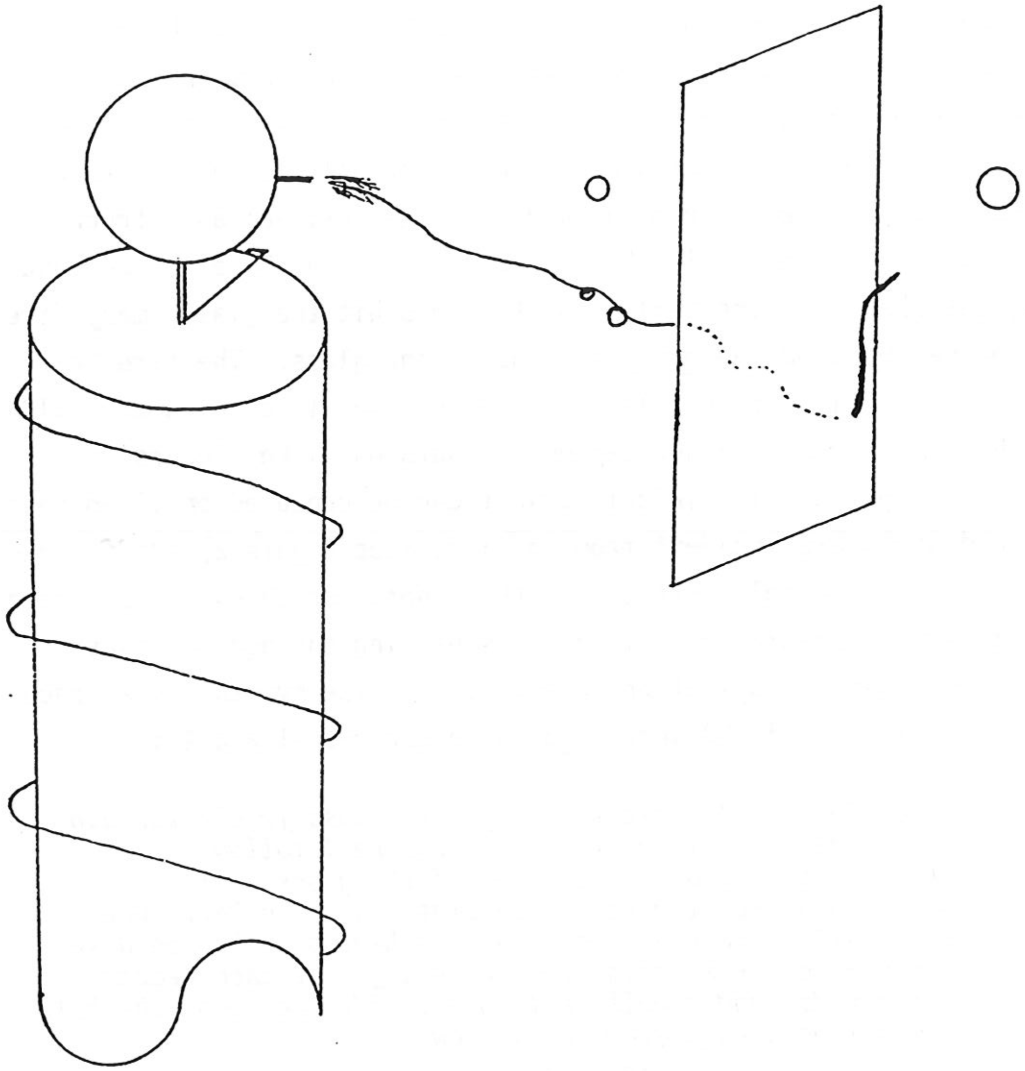


Figure 2. Isometric perspective of the low frequency (67 kHz) high voltage electrode and the glass windowpane seen in photograph 7. A fire ball and incident streamer appear on the left of the window. The streamer emerges on the right, where a second fire ball has been formed. Viewed in real time, the fire balls appear to be passing through the glass window.

lightning. We have photographically documented the "apparent" passage of fire balls through a glass windowpane in our laboratory experiments. (See Ref.4.) Using the above methods for producing fire balls, we set about creating conditions as described by observers of ball lightning. By having the streamers produced by the resonators strike a common glass windowpane with carbon smudges on it, we produced results normally found in nature. The observed streamers went from the high voltage terminal and struck the window glass. There were many fire balls present between the electrode and the glass, but when the fire balls and streamers hit the glass, many fire balls began emanating from the opposite side of the glass. The fire balls would then travel slowly horizontally 35 cm or so and flare up. Some would travel out a bit farther and either explode or burn out like cinders.

Photograph 7 is typical of what can be captured on video tape. Fire balls and streamers incident from the left (see Figure 2) are followed by streamers and fire balls created on the right. Watching the sequence in real time gives the appearance of fire balls passing through the glass.

The observed situation appears to fit the hypothesis advanced by Powell and Finklestein 20 years ago in References 41 and 42:

> "*Initially, electric lines of force pass freely through the glass. Positive ions from the ball follow force lines and pile up on one side of the glass while electrons from the room accumulate on the other. When the ball approaches, the glass is heated or broken down enough to become slightly conducting. It then becomes an electrode, and a ball is formed inside the room; the ball then floats away from the window.*"
>
> (Ref. 42)

The actual physics may be somewhat different, but the sequence of observations support the general idea. The relative ease of electric fire ball production by high voltage discharges in the presence of carbon films, smoke, ashes and dust is consistent with its natural observation in and around chimneys, where carbon is deposited in great profusion.

CONCLUSIONS

We believe that, as with the apparatus of Forrest and Witten, high current pulses from the copper wire and charred wooden electrodes on the high voltage terminal can be made to provide fractal bursts that quickly absorb ozone and other chemical reactants in the electrode region. When electrically ignited, the resulting charged aerogel structure gives the fire balls their characteristic properties.

This fractal nature of electro-chemical fire balls was first proposed and analytically explored with remarkable success by the Soviet Scientist B.M. Smirnov. There can be little doubt as to the similarity of the high voltage generated fire balls in our photographs and, either the 'engine room' fire balls produced by high current switches and relays, or the ball lightning produced naturally in atmospheric electrical storms.

Many years ago Finkelstein and Rubinstein concluded that, in all probability, "*... ball lightning has no relevance to controlled-fusion plasma research.*" (Ref. 43) It should now be apparent that this position can be experimentally supported. There is no need to call in either 'pathological science' or nuclear physics to understand these electro-chemical fire balls.

Perhaps one of the most obvious conclusions of our work is that Tesla's apparatus and method of fire ball production requires rather modest equipment. Now a host of experimenters may carry on fire ball generation and experimentation under their own controlled conditions. Best of all, the required apparatus is readily available in a multitude of existing laboratories around the world.

Finally, we call attention to the fact that the results reported in this paper thoroughly document Tesla's historic fire ball experiments. There can be no question now as to the authenticity of his 1899 accounts or the veracity of his fire ball observations.

CLOSING REMARKS

Tesla was not ambivalent concerning his visual observation and laboratory creation of electric fire balls at Colorado Springs. When describing his 1899 ball lightning research, he said,

> *"I succeeded in determining the mode of their formation and producing them artificially."* (Ref. 44)

It is unfortunate that he did not choose to share his experimental techniques with the scientific community at large during his lifetime. How fortunate we are that he left behind such extensive engineering documentation.

Just prior to closing his Colorado Springs Laboratory, Tesla wrote in his diary,

> *"A better knowledge of this phenomenon will be obtained by following up experiments with still more powerful apparatus which is in a large measure already settled upon and will be constructed as soon as time and means will permit."* (Ref. 45)

It is a matter of record that he returned to New York, started a huge transmitting station on Long Island, was pursued by his creditors and suffered financial bankruptcy before being able to complete the facility.

At long last, today, the fire balls can be closely studied in a controlled laboratory environment. We believe that the work which Tesla left undone may now be resumed. And, with the advanced techniques and concepts available to scientists today, rapid progress will surely be made.

It seems appropriate to close this paper with Tesla's own thoughts, conceived in the opening hours of the 20th century and recorded in his diary only a few days prior to departing for New York City from his lonely snow covered Colorado Springs laboratory. Concerning the fire balls, he wrote:

> *"It being a fact that* ***this phenomenon may now be artificially produced,*** *it will not be difficult to learn more of its nature."*
> N. Tesla
> January 3, 1900

How unfortunate for modern civilization that this then remote research facility, at the base of the Rocky Mountains, was closed forever in January of 1900, and the electrical wonders that were performed within its walls would remain a mystery until our generation.

APPENDIX

JULIA SETS, LIGHTNING AND DISCHARGES CONTAINING SPHERES

"*Fractal*" is a term coined by Benoit Mandelbrot to describe the shape and appearance of objects that have the properties of "self similarity" and "scale invariance". It is difficult to find a meaningful definition in simple words. Formally, a fractal is a figure whose Hausdorff dimension is not an integer.* Pragmatically, a fractal is a structure whose characteristic property is that little pieces of it are miniature copies of the entire object. Consequently, fractals are scale invariant physical or geometrical objects.

Mandelbrot studied the nonlinear (parabolic) iterative process described, for example, by the deceptively simple equation:

$$z_{n+1} = z_n^2 + C \qquad n = 0,1,2,3,\ldots \qquad \text{(A1)}$$

where $z = x+jy$ is a complex variable and C is a complex constant. Given a number z_0, square it and add the constant C to get z_1; then repeat to get z_2, z_3 and so forth. The Mandelbrot set is the set of all complex numbers C for which the size of $z^2 + C$ is finite even after an infinitely large number of iterations. Figure A1(a) shows a portion of the complex C-plane and the famous "Mandelbrot Bug" for regions where the sequence converges. The window on the complex plain extends over the region $-2.4<\mathrm{Re}\{C\}<0.8$, $-1.2<\mathrm{Im}\{C\}<1.2$.

Suppose we take $C = 0$. When one calculates the sequence given by Equation (A1), there are three possibilities, depending on z_0:

1. The numbers converge to zero. [Zero is called the *attractor* for this case, and all points at a distance less than 1 from the attractor are drawn into it.]
2. The numbers diverge to infinity. [All points greater than a distance of 1 are drawn into the attractor at infinity.]
3. The points are at a distance of 1 from zero and remain there. Their sequence lies on the unit circle, which in this case is the boundary between the two zones of attraction.

---

*Fractal dimension is defined as $d \ln M(R)/d \ln R$ where M(R) is the mass contained within a distance R from a typical point in the object.

We include the following simple program (written in QuickBasic 4.0) for those wishing to explore the complex C-plane and display their own Julia sets. At the prompt, enter C as a,b. Scale factors are suggested to make it fit your display.

FRACTAL.BAS

```
80  DECLARE FUNCTION ATN2! (num!, denom!)
90  REM "Fractals", by Peter SORENSEN, BYTE, September, 1984, pp. 157-172.
92  REM modifyed to display standard Julia Set by J.F. Corum, July 31, 1989
95  DECLARE FUNCTION ATN2! (num!, denom!)
100 CLS : PRINT "FRACTALS"
105 LOCATE 1, 55: INPUT "To start Press [ENTER]"; A$
110 SCREEN 0               '80 columns by 25 rows
120 CLS
125 CX = 320: CY = 240
130 x = .500001: y = 0
132 N = 0: k = 0
134 GOSUB 5000
138 FOR I = 1 TO 10: GOSUB 4000: NEXT
140 GOSUB 6000
160 GOSUB 4000
165 GOTO 140
170 END
1000 REM square root of x,y
1010 T = y
1020 S = SQR(x * x + y * y)
1030 y = SQR((-x + S) / 2)
1040 x = SQR((x + S) / 2)
1050 IF T < 0 THEN x = -x
1060 RETURN
2000 REM four over L
2010 S = LX * LX + LY * LY
2020 LX = 4 * LX / S
2030 LY = -4 * LY / S
2040 RETURN
3000 REM x,y times L
3010 TX = x: TY = y
3020 x = TX * LX - TY * LY
3030 y = TX * LY + TY * LX
3040 RETURN
4000 REM function of x,y
4010 GOSUB 3000
4020 x = 1 - x
4030 GOSUB 1000
4040 IF RND(1) < .5 THEN x = -x: y = -y
4050 x = 1 - x
4060 x = x / 2: y = y / 2
4070 RETURN
5000 REM get values
5020 LOCATE 1, 40: PRINT USING "[Present value (##.###,##.###)]"; CCX, CCY
5030 LOCATE 1, 1: PRINT "What is Const C (X,Y)"
5040 LOCATE 1, 22: INPUT ; CCX, CCY
```

```
5041 A = 1 - 4 * CCX: B = -4 * CCY
5042 DJ = (A * A + B * B) ^ .25
5043 EE = ATN2(B, A)
5044 IF EE < 0 THEN EE = EE + 6.283
5045 ET = EE / 2
5046 LX = 1 - DJ * COS(ET)
5047 LY = -DJ * SIN(ET)
5050 LLX = LX: LLY = LY
5060 GOSUB 2000
5070 CLS
5072 LOCATE 1, 40: PRINT USING "[Present value (##.###,##.###)]"; CCX, CCY
5075 LOCATE 2, 40: PRINT USING "[Present Value (##.#)]"; SSC
5080 LOCATE 2, 1: PRINT "What is scale (try 4,5 or 6)"
5090 LOCATE 2, 30: INPUT ; SSC: SC = SSC / 3
5094 SC = 2 * CX / SC
5096 RETURN
6000 REM plot x,y
6005 SCREEN 2    '640 X 200 pixils
6010 x% = (SC * (x - .5) + CX)
6020 y% = (CY - SC * (y)) / 2.4
6021 IF x% < 1 THEN GOTO 5070
6022 IF x% > 639 THEN GOTO 5070
6023 IF y% < 1 THEN GOTO 5070
6024  IF y% > 349 THEN GOTO 5070
6030    PSET (x%, y%)
6040 REM count points
6050 N = N + 1: k = k + 1
6052 IF k > 499 GOTO 6059: RETURN
6059 k = 0
6060 LOCATE 2, 65: PRINT USING "N =#######"; N
6065 LOCATE 23, 1: PRINT "[To stop press any key.]"
6070 ESC$ = INKEY$
6080 IF ESC$ <> "" THEN GOTO 7000
6090 RETURN
7000 LOCATE 25, 1: INPUT "To restart press [ENTER]"; A$
7010 GOTO 110

8000 FUNCTION ATN2 (num, denom)
8010 PI = 3.14159265#
8020 IF ABS(denom) < 1E-30 THEN atval = SGN(num) * PI / 2: GOTO done
8030 atval = ATN(num / denom)
8040 IF denom >= 0 THEN GOTO done
8050 IF num < 0 THEN atval = atval - PI ELSE atval = atval + PI
8060 done:
8070 ATN2 = atval
8080 END FUNCTION
```

Let us suggest a few complex points to explore:

C = .0001,.0001	(Ball)
C = 0, ±1	(Lightning)
C = -.1565,±1.0322	(Ball Lightning)
C = -.1, 0.95	(Fire Ball Bursts)
C = -1.2819,±0.4375	(Lightning with Dark Streamers)

BIBLIOGRAPHY

1. "Tesla Coils: 1890 to 1990 - 100 Years of Cavity Resonator Development", by K.L. Corum and J.F. Corum. (Elsewhere in these Proceedings).

2. **Colorado Springs Notes: 1899-1900**, by Nikola Tesla, edited by Aleksander Marincic, Nolit, Beograd, Yugoslavia, 1978, pp. 111, 330-333, 368-370, 372, 379-384, 431-433. (Abbreviated above as CSN)

3. **Fire Balls - A Collection of Laboratory Photographs**, (Text plus 38 photographs and commentary), by K.L. Corum, J.D. Edwards and J.F. Corum, Published by Corum & Associates, Inc., ISBN , 1988.

4. "Tesla's Production of Electric Fireballs", by K.L. Corum and J.F. Corum, Tesla Coil Builder's Association News, Vol. 8, No. 3, 1989, pp. 13-18.

5. "High Voltage RF Ball Lightning Experiments and Electro-Chemical Fractal Clusters", by K.L. Corum and J.F. Corum, Soviet Physics - Uspekhi, Vol. 160, No. 4, April, 1990, pp. 47-58.

6. "New Theory of Ball Lightning", by A.V. Zaitsev, Soviet Physics - Technical Physics, Vol. 17, No. 1, July, 1972, pp. 173-175. (Zh. Tekh. Fiz., Vol. 42, No.1, January, 1972, 213-216.)

7. "Formation of Ball Lightning", by B.M. Smirnov, Soviet Physics - Doklady, Vol. 21, No. 2, February, 1976, pp. 89-90. (Dokl. Akad. Nauk SSSR, Vol. 226, February, 1976, 806-808.)

8. "Analysis of the Nature of Ball Lightning", by B.M. Smirnov, Soviet Physics - Uspekhi, Vol. 18, No. 8, 1976, pp. 636-640. (Usp. Fiz. Nauk, Vol. 116, August, 1975, 731-739.)

9. "Possible Stabilization of High Ion Concentrations in Droplet Capacitors", by E.M. Golubev and I.V. Podmoshenskii, Soviet Physics - Technical Physics Letters, Vol. 3, No. 6, June, 1977, pp. 208-209. (Pis'ma Zh. Tekh. Fiz., Vol. 3, June 12, 1799, 509-512.)

10. "Absorption of Ozone by Porous Particles", by V.P. Afanas'ev, S.B. Dorofeev, V.I. Sinitsyn, and B.M. Smirnov, Soviet Physics - Technical Physics, Vol. 26, No. 11, November, 1981, pp. 1386-1389. (Zh. Tekh. Fiz., Vol. 51, Nov., 1981, 2355-2359.)

11. "Rapid Coagulation of Submicron Aerosols into Filamentary Three Dimensional Structures", V. Ya. Aleksandrov, I.P. Borodin, E.V. Kichenko, and I.V. Podmoshenskii, Soviet Physics - Technical Physics, Vol. 27, No. 4, April, 1982, pp. 527-529. (Zh. Tekh. Fiz., Vol. 52, April, 1982, 818-820.)

12. "Aerosol Mode of Ball Lightning", by V.Ya Aleksandrov, E.M. Golubev and I.V. Podmoshenskii, Soviet Physics - Technical Physics, Vol. 27,

No. 10, October, 1982, pp. 1221-1224. (Zh. Tekh. Fiz., Vol. 52, October, 1982, 1987-1992.)

13. "Estimation of the Parameters of a Chemical Model of Ball Lightning", by V.P. Krainkov, B.M. Smirnov, and I.P. Schmatov, Soviet Physics - Dokolady, Vol. 30, No. 7, July, 1985, pp. 587-589. (Dokl. Akad. Nauk SSSR, Vol. 283, July, 1985, 361-365.)

14. "Incandescent-Breakdown Multipoint Emission of Ball Lightning", by B.V. Voitsekhovskii and M.B. Voitsekhovskii, Soviet Physics - Doklady, Vol. 31, No. 3, March, 1986, pp. 247-249. (Dokl. Akad. Nauk SSSR, Vol. 287, March, 1986, 331-334.)

15. "Chromatography of the Combustion of Charcoal in Absorbed Ozone", by V.G. Plyukhin and B.M. Smirnov, Soviet Physics - Doklady, Vol.31, No. 4, April, 1986, pp. 321-322. (Dokl. Akad. Nauk SSSR, Vol. 287, April, 1986, 836-839.)

16. "Fractal Clusters", by B.M. Smirnov, Soviet Physics Uspekhi, Vol. 29, No. 6, June, 1986, pp. 481-505. (Usp. Fiz. Nauk, Vol. 149, June, 1986, 177-219.)

17. "Gasdynamics of Ball Lightning", by V.P. Krainov, G.P. Lebedev, A.O. Nazaryan, and B.M. Smirnov, Soviet Physics - Technical Physics, Vol. 31, No. 9, September, 1986, pp. 1066-1069. (Zh. Tekh. Fiz., Vol. 56, September, 1986, 1791-1796.)

18. "Electrical Phenomena in Ball Lightning", by B.M. Smirnov, Soviet Physics - Doklady, Vol. 32, No. 2, February, 1987, pp. 145-147. (Dokl. Akad. Nauk SSSR, Vol. 292, February, 1987, 1363-1367.)

19. "Aerogels", by B.M. Smirnov, Soviet Physics Uspekhi, Vol. 30, No. 5, May, 1987, pp. 420-432. (Usp. Fiz, Nauk, Vol. 152, May, 1987, 133-157.)

20. **Zagadka Sharovoy Molnii** (The Question of Ball Lightning), by B.M. Smirnov, Nauka, Moscow, 1987, 63 pp.

21. "Isolated St. Elmo's Fire on a Flying Concentrator and Ball Lightning", by B.V. Voitsekhovskii and M.B. Voitsekhovskii, Soviet Physics - Doklady, Vol. 32, No. 7, July, 1987, pp. 587-589. (Dokl. Akad. Nauk SSSR, Vol. 295, July, 1987, 580-582.)

22. "The Properties and the Nature of Ball Lightning", by B.M. Smirnov, Physics Reports, Vol. 152, No. 4, August, 1987, pp. 177-226

23. **Problema Sharovoy Molnii** (The Problem of Ball Lightning), by B.M. Smirnov, Moscow, Nauka, 1988, 208 pp.

24. "An Electrostatic-Chemical Model of Ball Lightning", by D. ter Haar, Physica Scripta, Vol. 39, June, 1989, pp. 735-740.

25. "High Temperature Institute to Host Seminar on Ball Lightning", by A. Gregoryev, Sovetskaya Litva, August 5, 1989, No. 179, pg. 4, Cols. 1-2.

26. **Fractals: Form, Chance and Dimension**, by B.B. Mandelbrot, Freeman, San Francisco, 1977. [Also see **The Fractal Geometry of Nature**, by B.B. Mandelbrot, Freeman, New York, 1983.]

27. "Long Range Correlations in Smoke-Particle Aggregates", by S.R. Forrest and T.A. Witten, J. Phys. A:Math. Gen., Vol. 12, No. 5, 1979, L109-L117.

28. "Diffusion-Limited Aggregation", by T.A. Witten and L.M. Sander, Physical Review B, Vol. 27, No. 9, May 1, 1983, pp. 5686-5697.

29. "Formation of Fractal Clusters and Networks by Irreversible Diffusion-Limited Aggregation", by P. Meakin, Physical Review Letters, September 26, 1983, pp. 1119-1122.

30. "Fractal Dimension of Dielectric Breakdown", by L. Niemeyer, L. Pietronero and H.J. Wiesmann, Physical Review Letters, March 19, 1984, pp. 1033-1036.

31. "Chaos, Fractals and Computers", by Keith Wood, Electronics World And Wireless World, October, 1989, pp. 957-966.

32. "Resource Letter FR-1: Fractals", by A.J. Hurd, American Journal of Physics, Vol. 56, No. 11, November, 1988, pp. 969-975.

33. "Julia Sets and the Mandelbrot Set", by A. Douady, in **The Beauty of Fractals**, by H.O. Peitgen and P.H. Richter, Springer-Verlag, Berlin, 1986, pp. 161-173.

34. **The Chemical History of A Candle**, by Michael Faraday,(last given in 1860), transcribed by Sir William Crookes, Edited by W.R. Fielding, E.P. Dutton and Company, 1920, pp. 52-58. Republished with index, commentary and 22 experiments by Chicago Review Press, 1988.

35. "Uber den Verlauf der electrischen Schwingungen bei den Tesla'schen Versuchen", A. Oberbeck, Wied. Ann., Vol. 55, 1895, pp. 623-632.

36. "A Technical Analysis of the Extra Coil As A Slow Wave Helical Resonator", with Kenneth L. Corum, **Proceedings of the 2nd International Tesla Symposium**, Colorado Springs, Colorado, 1986, Chapter 2, pp. 1-24.

37. "The Application of Transmission Line Resonators to High Voltage RF Power Processing: History, Analysis, and Experiment", **Proceedings of the 19th Southeastern Symposium on System Theory**, Clemson University, Clemson, South Carolina, 1987, pp. 45-49.

38. **Vacuum Tube Tesla Coils**, by J.F. Corum and K.L. Corum, Published by Corum & Associates, Inc., 1988, [100 page text, $55], ISBN 0-924758-00-7.

39. **TCTUTOR - A Personal Computer Analysis of Spark Gap Tesla Coils**, by J. F. Corum, D.J. Edwards and K.L. Corum, Published by Corum & Associates, Inc., 1988, [110 page text + Disk, $75], ISBN 0-924758-01-5.

40. N. Tesla as told to J. O'Neill, Unpublished chapter 34 of Tesla's biography, printed as "Tesla tries to Prevent World War II", Tesla Coil Builder's Association News, Vol. 7, 1988, No. 3, pp. 13-15.

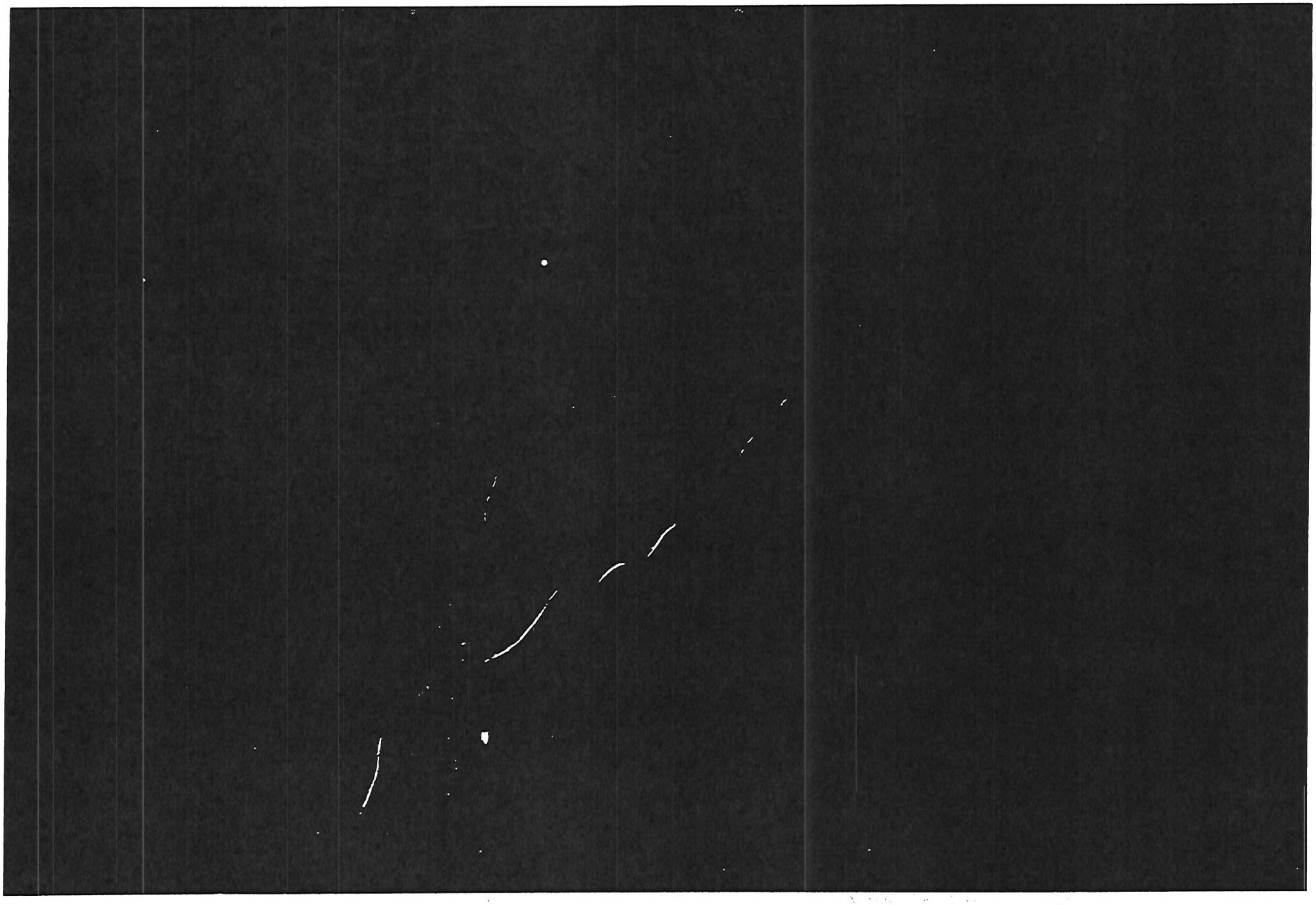
41. "Structure of Ball Lightning", by J.R. Powell and D. Finkelstein, in Advances in Geophysics, Vol. 13, (1969), Academic Press, pp. 141-189.

42. "Ball Lightning", by J.R. Powell and D. Finkelstein, American Scientist, Vol. 58, May-June, 1970, pp. 262-280. (See pg. 279.)

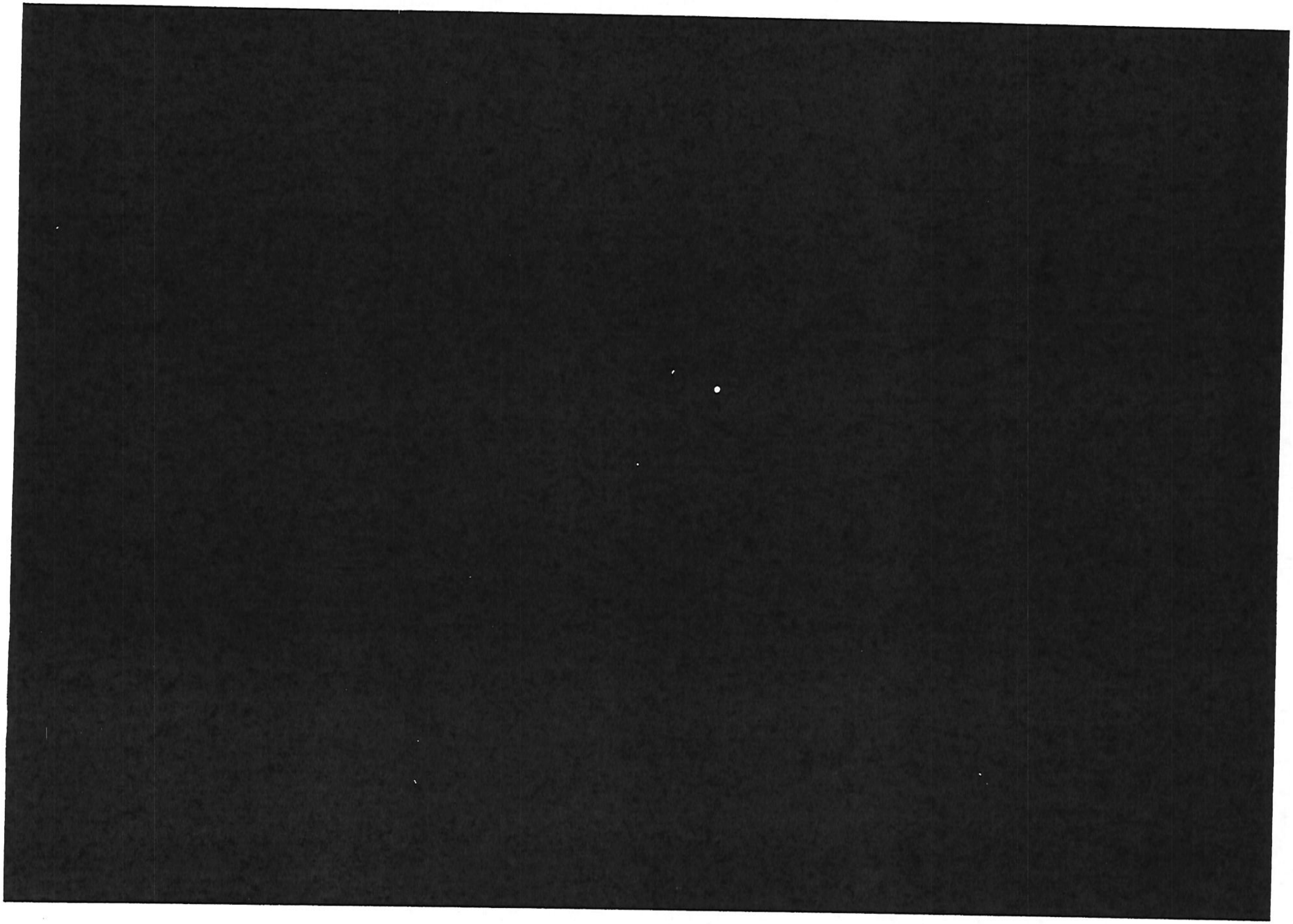
43. "Ball Lightning", by D. Finkelstein and J. Rubinstein, Physical Review, Vol. 135, No. 2A, July 20, 1964, pp. A390-A396.

44. "The Transmission of Electric Energy Without Wires", N. Tesla, Electrical World and Engineer, March 5, 1904, pp. 429-431.

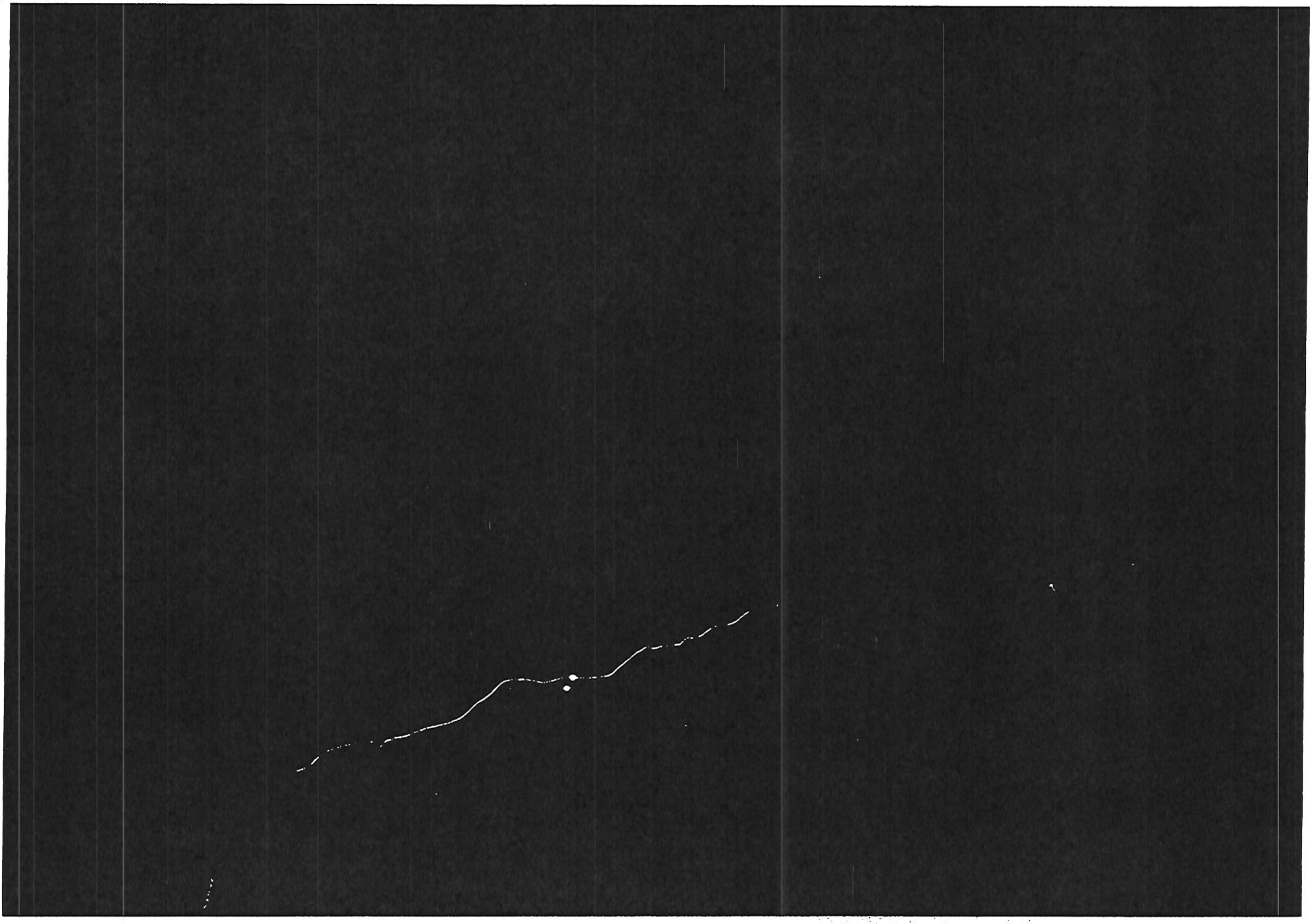
45. Reference 7, page 370.



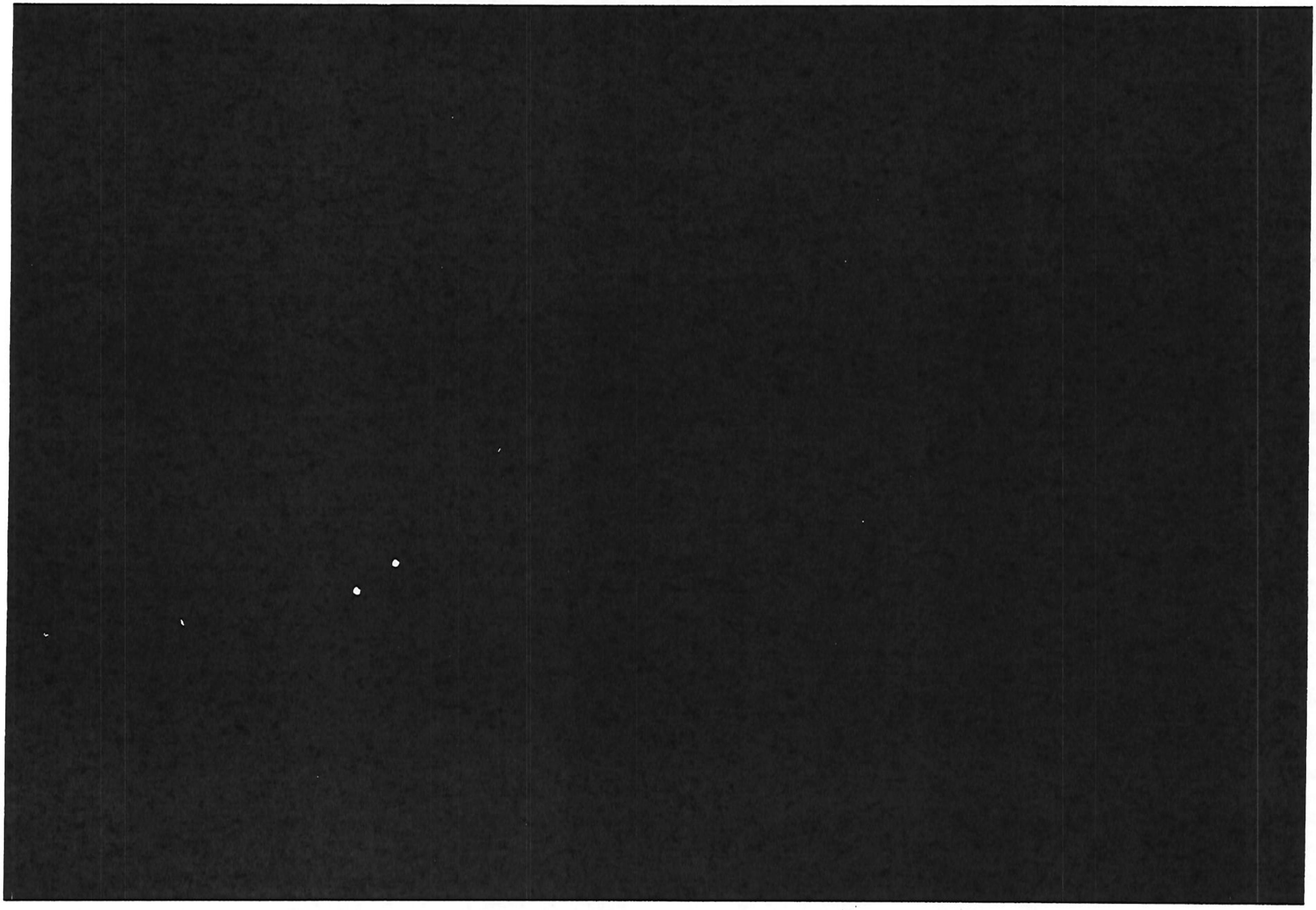
Photograph 1. An isolated 1 cm diameter fire ball "floating" in the midst of a spray of RF streamers.



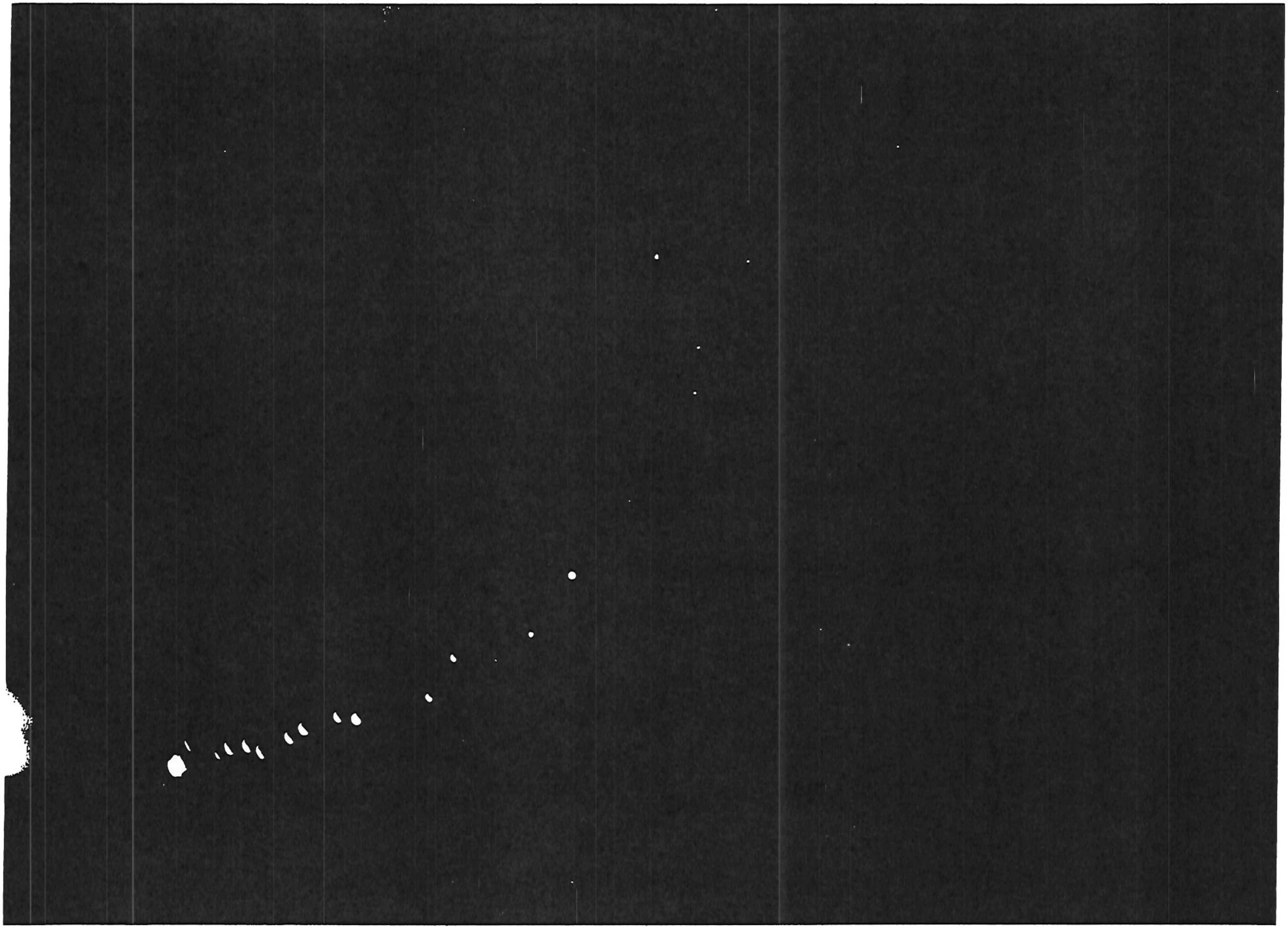
Photograph 2. Fire ball being struck by a high voltage RF streamer. The ball diameter is approximately 2 cm.



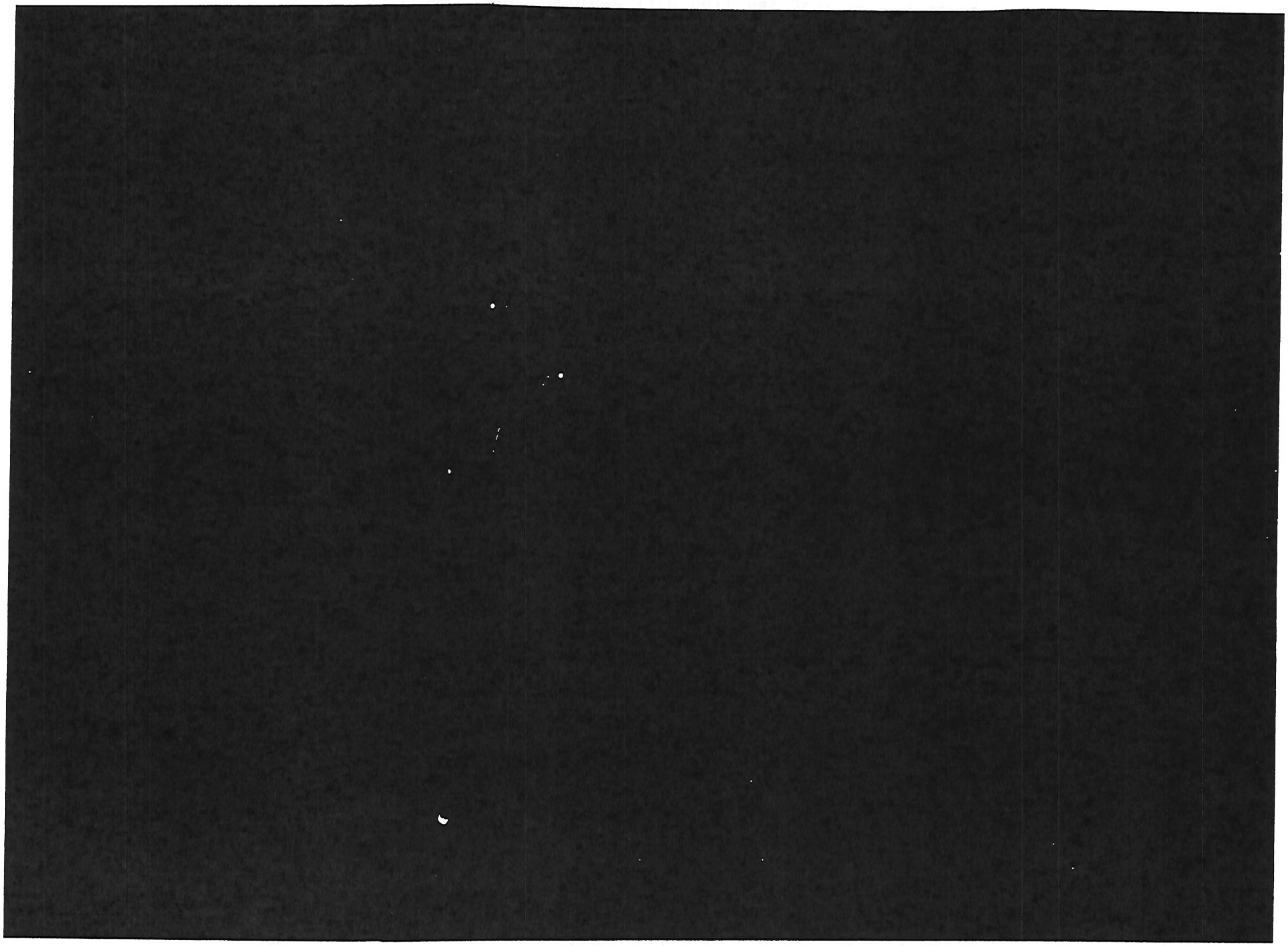
Photograph 3. Twin fire balls created in close proximity being struck by successive RF streamers. The fire ball diameters are on the order of 2 cm. The bright glow in the lower left is from the copper electrode attached to the high voltage terminal.



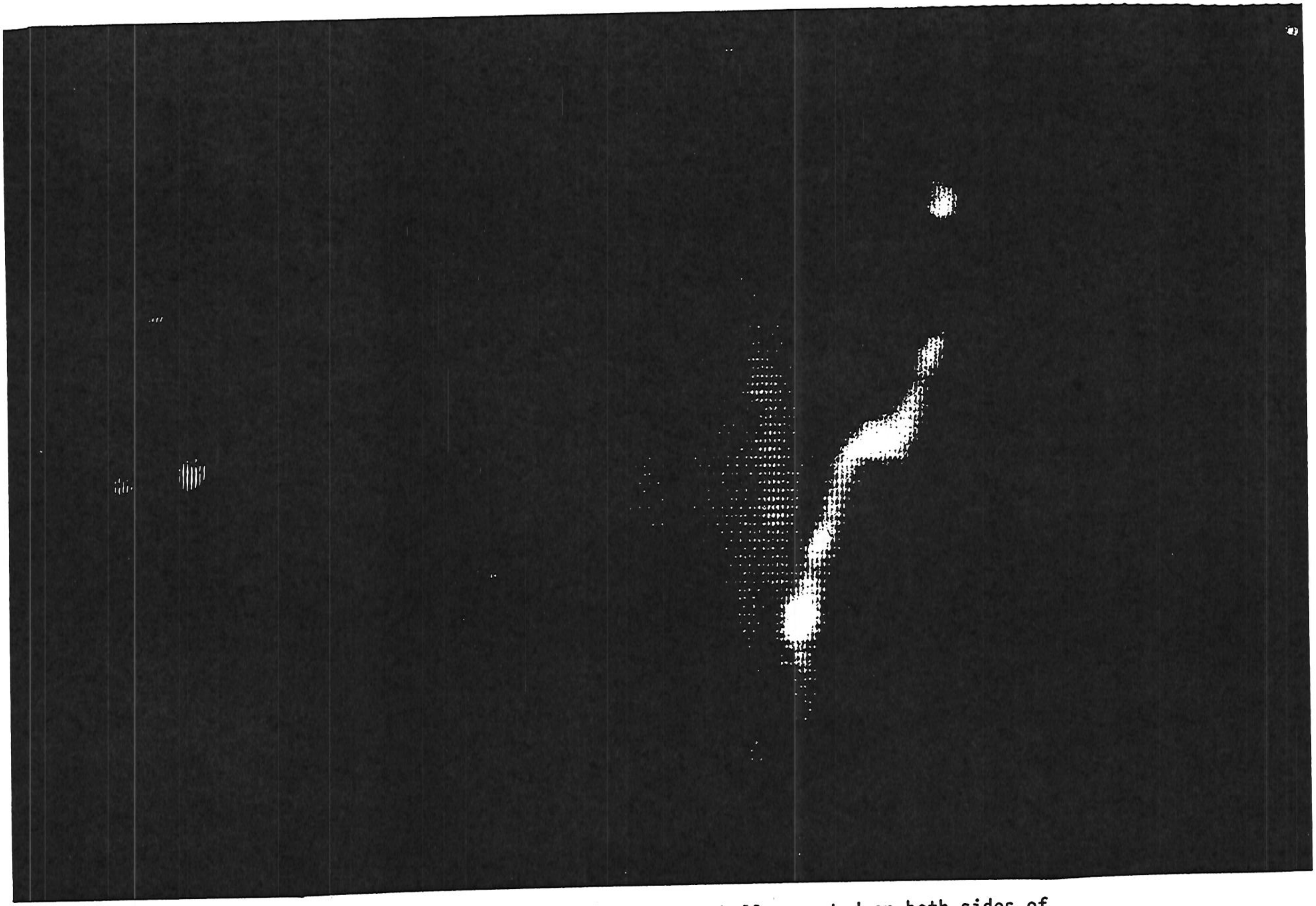
Photograph 4. Two large fire balls (2 to 3 cm in diameter) being struck in series by an RF streamer. The photograph was taken from a distance of 4 meters.



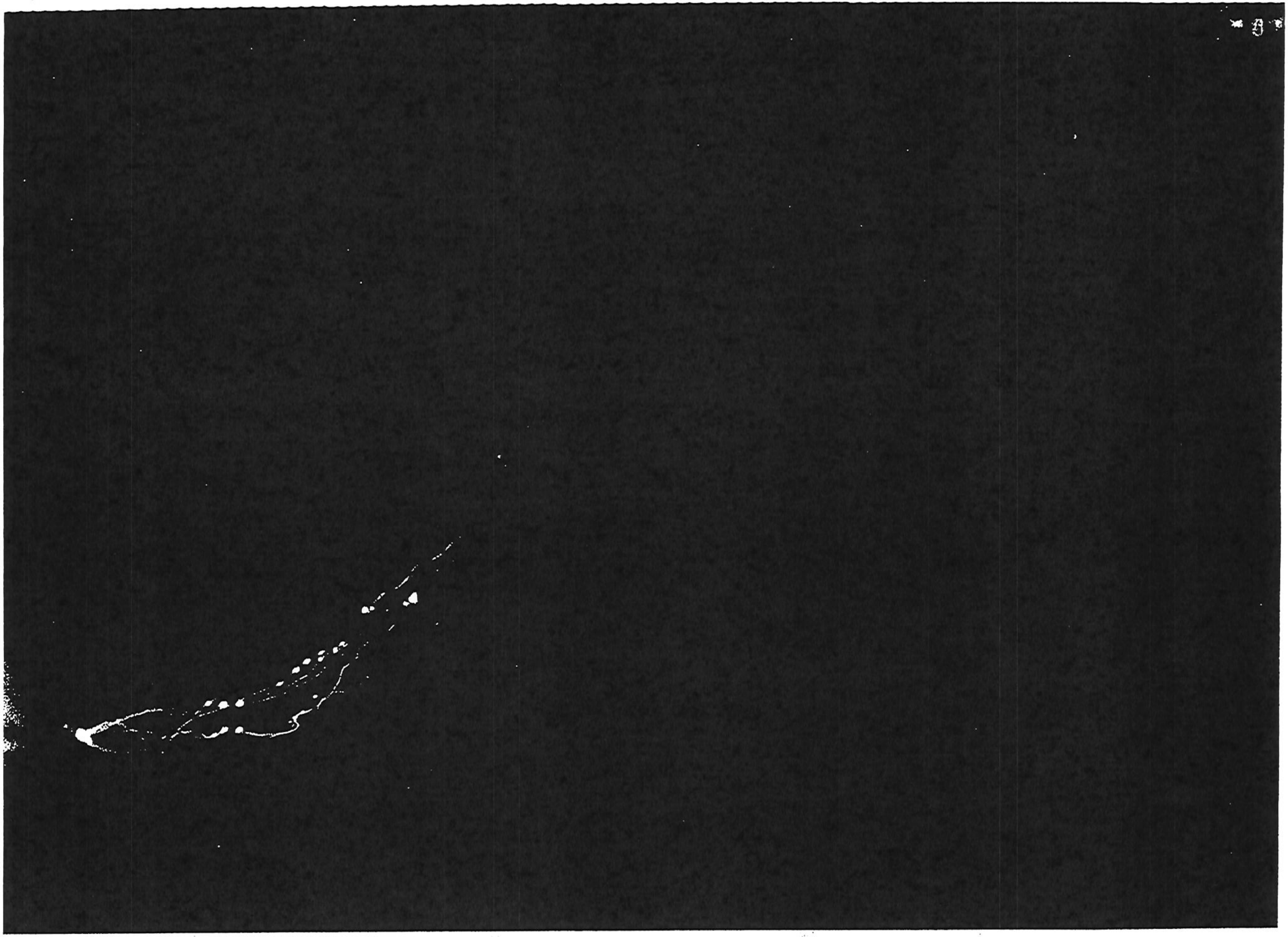
Photograph 5. A Spray of fire balls emanating from the high voltage electrode.



Photograph 6. Four fire balls being struck by RF streamers.



Photograph 7. A dynamic photograph of fire balls created on both sides of a glass window. On the left one can see three floating fire balls and a faint streamer. The streamer has just struck the window and is now decaying on the left hand side yet it is still quite strong on the right hand side of the window, where another fire ball has just been created and is moving upward and off to the right from the glass. The photo was taken from a video recording of the phenomenon.



Photograph 8. The arcane hue of these RF discharges and a dozen variously colored glowing electric fire balls recall Tennyson's famous lines from Locksley Hall. See them "glittering like a swarm of fireflies tangled in a silver braid."